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ON GRB PHYSICS REVEALED BY FERMI/LAT

ZHUO LI

Department of Astronomy/Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China

Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China

zhuo.li@pku.edu.cn

We discuss the implications of Fermi/LAT observations on several aspects of gamma-ray burst (GRB) physics, including the radiation process, the emission sites, the bulk Lorentz factor, and the pre-shock magnetic field: (1) MeV-range emission favors synchrotron process but the highest energy ($>$ 10 GeV) emission may not be synchrotron origin, more likely inverse Compton origin; (2) GRB should have multi-zone emission region, with MeV emission produced at smaller radii while optical and $>$ 100 MeV emission at larger radii; (3) the bulk Lorentz factor can be a few 100's, much lower than 10^3, in multi-zone model; (4) the upstream magnetic field of afterglow shock is strongly amplified to be at least in mG scale.

1. Introduction

After decades of research we have deeper and deeper understanding on the nature of gamma-ray bursts (GRBs). In order to solve the compactness problem, it is long believed that cosmological GRBs should be produced by relativistically expanding outflow with Lorentz factor (LF) $\Gamma > 10^2$. The outflow is likely in a jet configuration, based on the energy argument in some cases of GRBs with huge energy $E_{iso} > 10^{54}$erg, and based on observations of light curve breaks in optical afterglows. However, beyond that very little is known about the prompt emission, e.g., the launch of the relativistic jet, the jet composition, the energy dissipation, and the radiation mechanism, etc. In comparison, the afterglow phase seems to be clearer. It is widely believed that the bulk afterglow emission is mainly produced by a relativistic shock propagating into the circum-burst medium, generating high energy electrons which produce afterglow emission by synchrotron radiation. However, the particle acceleration process in the shock is still poorly understood.

Thanks to its high sensitivity in high energy range and wide field of view, Fermi/LAT bringed us a brand new window to observe GRBs. I will discuss, in my point of view, the implication of LAT observations on GRB physics, including the radiation process, the emission sites, the bulk LF and the pre-shock magnetic field.

2. Main LAT Discoveries

By the LAT observations of the past 3 years, many new features of high energy emission in GRB prompt-burst and early-afterglow phases were discovered (see also Ref. 1, 2 for an over view). (I) In most LAT observed GRBs the onset of high energy (LAT) emission is delayed, e.g., by few seconds for long GRBs 080916C[3] and 090902B[4] and 0.2 s for short GRB 090510[5]. (II) In general the high energy emission is extended well beyond the end of MeV emission, e.g., up to 10^3s in long GRBs 080916C and 090902B and up to 10^2s in short GRB 090510. (III) In the brightest bursts, high energy photons are detected up to tens of GeV, e.g., GRBs 080916C, 090510, 090902B, and 090926A[6]. (IV) In most LAT bursts the time-integrated spectra show single "Band components" up to a few 10's GeV, e.g., GRB 080916C, while some cases show additional high energy components with hard spectral indices, e.g., long GRB 090902B and short GRB 090510. However, the νF_ν spectra still peak at MeV range.

3. Implications by LAT

3.1. *Radiation process in prompt emission*

The huge energy released in gamma-rays by GRBs, typically $\gtrsim 10^{53}$erg, suggests that the radiation processes should be efficient, otherwise there may be energy crisis given the limited gravitational energy available in a stellar explosion. The most favored radiation processes are synchrotron and inverse-Compton (IC) radiations by electrons. There are already some expectation before the launch of Fermi mission that there may be a high energy bump in high energy due to IC emission. However, Fermi observations, given its wide energy range, over 7 decades, show that most GRBs only have single Band component, and even for those GRBs with additional high energy components, the νF_ν flux peaks at MeV range. If the GRB emission is dominated by MeV emission, the radiation process responsible to MeV emission favors synchrotron radiation over IC one[7,8]. This is because if the MeV photons are produced by IC scattering of lower energy photons, the upscattering of the MeV photons (second order IC) will produce higher energy component with even higher flux. Ref. 9 analyzes GRB 080916C specifically, and concludes that if MeV emission is produced by IC and the second order IC component is beyond the LAT energy range (in order not conflicted with LAT observation), the required energy should be larger than MeV emission energy by several orders of magnitude, raising the energy crisis. Thus Fermi observations favor *synchrotron process* over IC as the radiation mechanism of MeV emission.

However, the highest energy emission may not be synchrotron origin. The maximal synchrotron photon energy is limited by the fact that the electron acceleration time is shorter than the synchrotron cooling time. This argument can be transferred into a lower limit to the bulk LF of GRB outflow. As detected by LAT, high energy emission in bright GRBs extends to tens GeV scale with hard spectrum, it is rea-

sonable to believe that the spectral cutoff, if exist, should be $\gtrsim 10^2$GeV[a], which, if having synchrotron origin, implies a bulk LF of $\Gamma \gtrsim 10^4$[10]. Such high LF may not be available for GRB jets, then the synchrotron origin of the LAT detected highest energy photons may not be true[10]. Other mechanisms are required to produce the observed $\gtrsim$ 10GeV photons, likely to be IC origin, e.g., IC emission from residual internal shocks[10].

It should be emphasized that the explanation of the GRB prompt spectra is still an open question. In particular, the hard spectra below break energy, especially in some GRBs with spectra harder than $f_\nu \propto \nu^{1/3}$, are inconsistent with optically-thin synchrotron radiation, which has been argued not in favor of synchrotron but alternative processes, e.g., "photosphere" emission[11]. However, there are already efforts in producing hard spectrum from synchrotron process[12,13,7], and the detection of high polarization in GRB prompt emission does support synchrotron origin[14].

3.2. *Prompt emission sites*

LAT detects that in GRB 080916C *the bulk emission of the second light-curve peak is moving toward later times as the energy increases* (see time bin b in Fig 1 and its inset panels in Ref. 3), and the time delay of 100-MeV emission is about 1 s relative to MeV emission. Note this is much larger than the MeV variability timescale, < 100 ms[15]. In short GRB 090510, the cross correlation analysis also show that the LAT emission is delayed relative to MeV emission, with delay time, ~ 0.2s, larger than the ms-scale MeV variability time by orders of magnitude[5].

The fact that the high energy delay time is larger than low energy (MeV) variability time by orders of magnitude,

$$t^H_{delay} \gg t^L_{var},$$

is naturally explained by multi-zone emission regions, i.e., the low energy emission is produced at small radii, $R_L \lesssim \Gamma^2 c t^L_{var}$, while the high energy one produced at larger radii, $R_H \sim R_L + \Gamma^2 c t^H_{delay} \gg R_L$. In addition, there is also evidence of multi-zone emission region in optical observations. GRB 080319B shows optical time delay of 2 s relative to MeV emission[16], larger than MeV variability time by orders of magnitude, $t^{opt}_{delay} \gg t^L_{var}$. This also suggests that optical emission is produced at a region with radii much larger than MeV radii, $R_{opt} \sim R_L + \Gamma^2 c t^{opt}_{delay} \gg R_L$.

The above time delay features are consistent with the residual collisions[17,10] in the framework of internal shock models. After first generation collisions which produce MeV synchrotron emission, the residual shell-shell collisions continue taking place, smearing out the velocity fluctuation in the outflow. The residual collisions accelerate electrons which produce longer wavelength synchrotron emission, and

[a]A spectral fit to GRB 080916C spectrum using exponential cutoff at high energy actually results in a cutoff energy of $E_{cut} > 100$ GeV, much larger than the detected highest energy photon (B. Li and Z. Li, 2011, subm).

generate high energy emission by IC scattering since the outflow is under bath of the inner-origin MeV photons[17]. The high energy delay is due to that the higher energy photons can only avoid $\gamma\gamma$ absorption at larger radii[10].

The large delay time implies that one-zone (one-radius) models do not work. However the argument does not hold in models where the emission region is highly angularly inhomogeneous and $R_L \lesssim \Gamma^2 c t_{var}^L$ is not necessary[18,19,20]. But the high energy delay still needs to be explained in these models.

3.3. *Bulk Lorentz factor*

High energy, > 10 GeV, photons are often detected by LAT, which, based on opacity argument, leads to more stringent constraint on bulk LF, $\Gamma > 10^3$, much larger than previously thought. If E_{cut} is much higher than the energy of observed highest energy photons, even larger LF is required. However, this is still based on one-zone assumption. As the high energy time delay suggests mult-zone emission sites, this assumption should be relaxed. In a two-zone picture, where GeV photons are produced at large radii and attenuated by inner-originated MeV photons, the bulk LF is much lower, i.e., a few hunderds[21,22]. In addition, based on the residual collision model, the 1 s scale time delay of > 100 MeV emission in GRB 080916C suggests a typical value of bulk LF, $\Gamma \sim 300$[10]; the detection of spectral cutoff in GRB 090926A also suggest that the LF is only a few hundreds[6]; moreover, the geometry effect can reduce the LF limit[23].

3.4. *Pre-shock magnetic field of afterglow shocks*

The LAT extended emission show a power law decay and spectral index of about $f_\nu(t) \propto \nu^{-1} t^{-1.3}$. The light curve slope, spectral index and flux level are consistent with the synchrotron afterglow model. Even though it may not be true that the whole burst is dominated by forward shock emission (as discussed in section 3.1), for the 10^3s-scale emission the forward shock emission is still most favored over other possible models (see a discussion in the introduction of Ref. 24).

In order for Fermi shock acceleration works, the electrons that emitting LAT emission should survive the upstream radiative cooling due to IC scattering the afterglow photons. This require a short upstream residence time, i.e., the upstream magnetic field should efficiently deflects the electron trajectory[25]. For > 100 MeV photons at 10^3s scale, the upstream magnetic field is required to satisfy $B_u > 10^0 n_0^{9/8}$mG[26], where n_0 is the preshock density in unit of 1 cm^{-3}, more stringent than the previous constraint by X-ray afterglow observations on day scale[25]. This suggests that the preshock magnetic field is strongly amplified[b], most likely by the streaming of high energy shock accelerated particles.

[b]Following the same argument Ref. 27 results in much lower B_u limit because they assume an uniform, ordered upstream magnetic field, which optimizes much the deflection of electrons.

4. Summary

LAT observations help to reveal the following facts in GRB physics: (I) The radiation process responsible to MeV range emission favors synchrotron over IC radiation, however the highest energy emission may not be synchrotron origin, but likely IC radiation. (II) The bulk GRB emission is multi-zone origin, with MeV emission produced at smallest radii while long wavelength (e.g., optical) and high energy emission produced at larger radii. (III) The bulk LF can be a few 100's if relaxing the one-zone assumption for the emission region. (IV) The upstream magnetic field of afterglow shock is at least in mG scale, implying strong amplification of pre-shock magnetic field.

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